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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Russell M. Cummings

Title: Aerodynamics Education: Where We've Been and Where We're Going

Circle one: Abstract Tech Report Journal Article Speech Paper Presentation Poster

Thesis/Dissertation Book Other: ______________

Check all that apply (For Communications Purposes):

[] CRADA (Cooperative Research and Development Agreement) exists

[] Photo/ Video Opportunities [] STEM-outreach Related [] New Invention/ Discovery/ Patent

Description: This is an invited paper describing my opinions about the current status and future needs for aerodynamics education.

Release Information:

Previous Clearance information: (If applicable) None

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3. DISCUSSION.
The paper will be presented at the AIAA Applied Aerodynamics Conference in San Diego, CA

4. RECOMMENDATION.

(signature)
Thomas E. McLaughlin, PhD, DFAN
Professor

Aerodynamics Education: Where We've Been and Where We're Going

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In a quarter century of teaching aerodynamics, I have seen incredible changes in our collective educational approach. Previously, there were time honored theories, a very few textbooks, dated but interesting movies showing fluid flows, and relatively straight-forward experiments to reinforce a few concepts. Currently, a wealth of information is available to the aerodynamics educator, including those same theories, a number of excellent textbooks, a wide spectrum of computational aerodynamics codes and associated multimedia visualizations, and ever-improving experimental approaches for measuring and visualizing fluid flows. An important question remains, however, and that is whether all of these changes have led to students who understand aerodynamics any better than they did decades ago. While empirical data may not be available to answer that question, this paper will delve into the difficult concepts contained in aerodynamics, and lead to the conclusion that effective aerodynamics education requires an integrated, broad approach based in fundamentals that takes full advantage of a variety of approaches in order to most effectively educate students. Hopefully we will come to a better understanding of the answer to the question, "what do our students need to know about aerodynamics, and when do they need to know it?"

I. Introduction

THE history of aerodynamics education is probably deserving of a detailed historical treatment, and I by no means believe that this paper is that treatment. Perhaps, however, this is a first step toward re-thinking how we teach aerodynamics based on how we have done it in the past, and how we might be able do it in the future. What really forms the basis of this paper, however, is a conversation I had with Robert Kelley-Wickemeyer, Chief Engineer of Aerodynamics at Boeing, while I was a Boeing/Welliver Faculty Fellow in the year 2000. My question was quite simple: "how much of what undergraduate students are taught in aerodynamics courses is used in industry?" His answer was also simple, but very challenging: "As much as I hate to say it, because I love the classical theories of aerodynamics, we use very little that students learn about aerodynamics here at Boeing." For some reason, that answer both worried me and thrilled me. It worried me because I knew that the hundreds of lectures I had given over the years on aerodynamic theory were largely useless, but it thrilled me because I realized that there was a great opportunity to improve and evolve aerodynamics education in the future.

I was not the only person reaching this realization. A number of faculty at a variety of universities, many of whom had experience in the aerospace industry, realized that the computational capabilities that existed at that time might be ready to bring into the undergraduate realm.[1-8] But how could that be accomplished with a field that was largely considered to be an area of graduate study? Also, how would the large population of faculty who had not spent time in applied research pursuits be persuaded to give up their beloved aerodynamic theoretical developments? In fact, most of those faculty probably wanted their undergraduates to learn about theoretical developments to better prepare them for life as a graduate student, where theoretical development was still a possible avenue of research. There were also engineers in industry calling for an evolution of aerodynamics, and they probably hoped (perhaps wishful thinking) that universities might help in this process.[9-10]

This conundrum leads me to consider the question, "What is the purpose of aerodynamics education?" Of course, there are many answers to that question, but those answers probably fall into a few broad categories. Some faculty believe that the majority of their students are going to work as engineers in the aerospace industry and might take a very applied view in their answers.[11] Other faculty, who see their primary job as preparing graduate students for research, might take a more theory-based view in their answers.[12] However, when you read these papers you will

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quickly realize that there is a broad overlap between everyone's "list" of important topics to be included in an aerodynamics course.

For example, Mason[11] polled the members of the AIAA Applied Aerodynamics Technical Committee in 1992 and asked them the following questions (among others): 1) What do you think are the most important fundamental aerodynamic ideas that a new grad should know?, and 2) What are the most important items on an applied aerodynamics literacy list for new grads? The answer to the first question was almost universally, "knowledge of flow physics." Interestingly, that answer would almost certainly also be a top reply from faculty at graduate schools. The answers to the second question, however, were quite varied and included:

- equations of fluid motion: Navier-Stokes and Euler equations, etc.
- flow physics: vortex flows, viscous dominated flow, compressibility, unsteady aerodynamics, and turbulence
- experimental and computational approaches and how to assess their accuracy
- panel methods (and other potential flow approaches)
- aerodynamic prediction methods
- aircraft nomenclature
- performance
- tradeoffs
- familiarity with applied mathematics and numerical methods

Apparently not one respondent specifically listed a classical aerodynamic theory (like thin airfoil theory or lifting-line theory). Rather, there was a strong emphasis on understanding fluid flow physics and practical concepts of using aerodynamics within the context of aircraft design. But are these the topics in a typical university undergraduate aerodynamics course? And how do you get a "knowledge of flow physics" in order to be a good aerodynamicist? Answering these questions is the topic of this paper, which we will look at first from an historical perspective, and then by looking at the future to explore how we might evolve.

II. Where We've Been

In order to understand where we've been, we will first look at a group of professors who were known for their ability to understand fluid/aerodynamics and also see how they learned and taught. This is by no means an exhaustive list of important aerodynamics professor researchers; I chose these individuals because each of them made discoveries or development important to aerodynamics and also were university teachers. There are certainly many other who should be included! But, perhaps we can learn a little about what was going through the minds of these luminaries as they conducted their research, and also see how well they were able to convey their understanding to students in the classroom. We will also consider how a typical aerodynamics course has been taught for the past thirty years or so, and see what we can learn from comparing our observations.

A. Osborne Reynolds

Osborne Reynolds (1842-1912) was a leading fluid dynamicist in the late 19^{th} century and into the 20^{th} century, initially at the University of Manchester and later at Cambridge University. His most famous contributions to aerodynamics include his experiments with laminar-turbulent transition, the definition of the non-dimensional parameter to define transition (the Reynolds number) and the formulation of Reynolds stresses which are important to modern CFD codes.

Reynolds was a gifted researcher and made very important fundamental contributions to aerodynamics, but how did he accomplish those achievements? According to A.H. Gibson, "Reynolds's approach to a problem was essentially individualistic. He never began by reading what others thought about the matter, but first though this out for himself. The novelty of his approach to some problems made some of his papers difficult to follow, [but his] more descriptive physical papers . . . make fascinating reading, and when addressing a popular audience, his talks were models of clear exposition."[13] thought

This approach served Reynolds well, especially as he started and continued his important testing of laminar/turbulent transition in his water channel, shown in Fig. 1. His detailed and exhaustive experiments clearly showed when a laminar stream transitioned to a turbulent flow, and his physical observations and understanding led him to create the non-dimensional number that described the flow he was observing, which we now call the Reynolds number.

But Reynolds was not only historically significant because of his research, he was also important for the applied mathematics course he created at Manchester, something which was quite new and innovative at the time. Anderson states that, "Reynolds was a scholarly man with high standards. Engineering education was new to English universities at that time, and Reynolds had definite ideas about its proper form. He believed that all engineering students, no matter what their specialty, should have a common background based in mathematics, physics, and particularly the fundamentals of classical mechanics. ... Despite his intense interest in education, he was not a great lecturer. His lectures were difficult to follow, and he frequently wandered among topics with little or no connection. He was known to stumble upon new ideas during the course of a lecture and to spend the remainder of the time working out how those ideas at the blackboard, oblivious to his students. He did not spoon-feed his students, and many did not pass his course, but the best students enjoyed his lectures and found them stimulating, such as J.J. Thomson, who in 1906 received the Nobel Prize in physics for demonstrating the existence of the electron."[13]

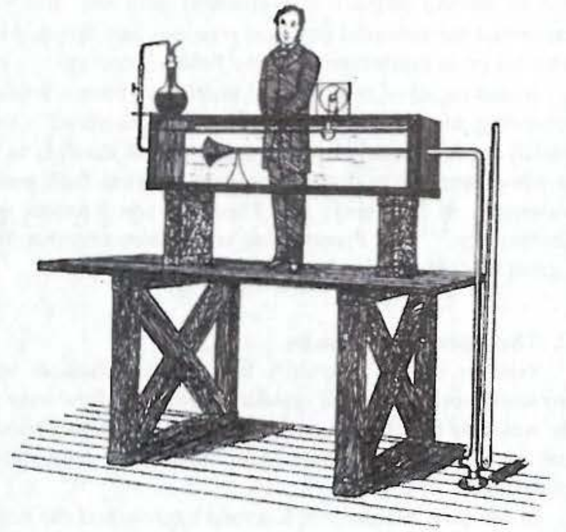

Figure 1. Reynolds' laminar/turbulent transition experiment, c. 1883.

So, what have we learned about Reynolds? He was an important researcher who depended on his physical observations in order to create improved understanding. His theoretical concepts typically followed his physical observations and collection of data and were not mathematically complex. He strongly believed in common course work for engineering students, but apparently he was not a good teacher (at least for most students). Keep these characteristics in mind as we proceed to our next professor.

B. Ludwig Prandtl

Ludwig Prandtl (1875-1953) was a German professor at Göttingen University who made some of the most important discoveries in aerodynamics, including the concept of the boundary layer and wing theory, among many others. He had a large number of successful students, including Ackeret, Betz, Blasius, Busemann, Den Hartog, Küchemann, Munk, Pohlhausen, Schlichting, Tietjens, Timoshenko, Tollmien, and Von Kármán. In fact, according to the Mathematics Genealogy Project,[14] Prandtl had at least 88 doctoral students and over 3000 academic descendants (whose numbers are still increasing). His impact on aerodynamic theory development is profound and continues to the present time.

But how did Prandtl discover new ideas and turn them into aerodynamic concepts? According to Bodenschatz, and Eckert, "He always attempted to gain 'a thorough visual impression' about the problems with which he was concerned."[15] In fact, Prandtl said that, "The equations come later when I think that I have grasped the matter."[16] "By the same token, Prandtl's approach to theory relied heavily on practice. For that matter, practice could be an observation of flow phenomena in a water channel, an *experimentum cruces* like the trip-wire test, or a challenge posed by practical applications such as skin friction."[15] An example of a physical visualization that Prandtl used to create a theory are the airfoil vortices shown in Figure 2,[17] where an airfoil start-up vortex is shown.

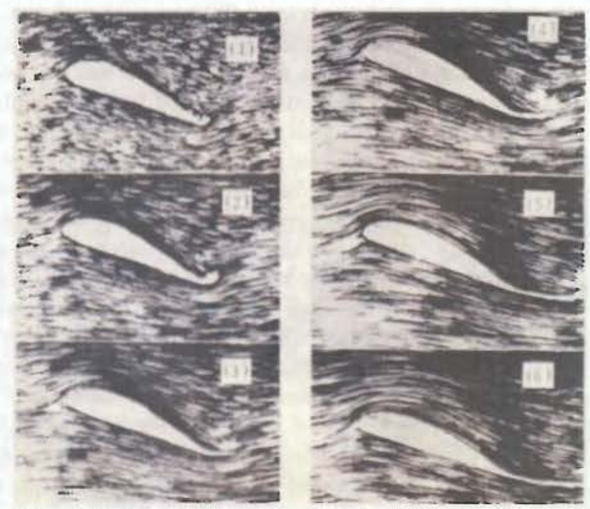

Figure 2. Prandtl's photograph of the airfoil start-up vortex.[17]

In fact, his student von Kármán said, "Prandtl, an engineer by training, was endowed with rare vision for the understanding of physical phenomena and unusual ability in putting them into relatively simple mathematical form. His control of mathematical methods and tricks was limited; many of his collaborators and followers surpassed him in solving difficult mathematical problems. But his ability to establish systems of simplified equations which expressed the essential physical relations and dropped the nonessentials was unique, I believe, even when compared with his great predecessors in the field of mechanics—men like Leonhard Euler and d'Alembert."[18]

Based on all of this, Prandtl must have been a brilliant teacher of aerodynamics in the classroom. Unfortunately, according to Anderson, "Prandtl was considered a tedious lecturer. He could hardly make a statement without qualifying it. Nevertheless, he expected his students to attend his lectures, and he attracted excellent students, many of whom went on to distinguish themselves in fluid mechanics, such as Jakob Ackeret in Zürich, Switzerland, Adolf Busemann in Germany, and Theodore con Kármán in Aachen, Germany, and later at the California Institute of Technology,"[13] So, Prandtl also was a keen observer and proponent of understanding physical mechanisms, but not a great teacher of what he had learned.

C. Theodore von Kármán

Perhaps one of Prandtl's best known students was Theodore von Karman (1881-1963), who deduced the physical mechanism and stability theory for flow over a cylinder (as shown in Fig. 3), among many other things.[19] He was able to solve this problem in a very short period of time (in fact, this was not his research project but that of one of Prandtl's students) with incredible perception and knowledge of physical concepts and mathematical modeling.

In his own words, von Kármán approached the solution this way: "In such problems one starts with assumptions. I assumed that the water rolled up into vortices as it passed over and under the cylinder and broke off into two trails, one from the top and one from the bottom. Then I considered two possibilities. First I assumed that the vortices are all symmetrical, that is, the top and bottom vortices form at the same time and start out together. But the mathematics of this motion soon told me that it was unstable. A very small deviation in the position of the vortices would gradually grow larger until the flow pattern was destroyed."

Figure 3. Prandtl's photograph of the von Kármán Vortex Street.[19]

"Then I made a second assumption in which the vortices are shed alternately from the top and bottom of the cylinder. One vortex is formed on the top, then one at the bottom, one again on the top, one again on the bottom, and so on. As I examined this motion, the whole solution suddenly leaped into my mind and I saw clearly that the configuration becomes stable when there is a definite geometric arrangement of the vortices. This arrangement occurs only at a certain relationship of two distances—the distance between two single consecutive vortices and the distance between the two rows of vortices. Or to put it another way, instead of marching two by two, the vortices are staggered like lampposts along both sides of a street."[20]

In addition to being an incredible researcher, von Kármán was also a very good teacher. In fact, upon arriving at Cal Tech he noticed that the typical classroom approach, "was somewhat conventional. Each day so many pages of study were assigned from a textbook. The teacher wrote equations on the blackboard. The students copied them fervently in his notebook while he tried to understand as much of the reasoning as he could. There were frequent examinations in some courses. Therefore it was the memory, not creative impulses of the mind that was being trained. Of course under such circumstances the teacher would be barely remembered."

"My years of teaching had given me a different view of the art. In Germany, as I've indicated earlier, my courses began with the basic concepts, so the students would quickly develop a feeling for the principle at work. For me the principle was most important, not the detail, and I subsequently emphasized this in class at Cal Tech. How does the electron "feel" in its environment? What makes it behave as it does? What makes the wing lift in the air? First in each case came the physical "picture" with only the essentials, like a caricature. Then comes the mathematics."[20]

The best summary of von Kármán's ability to teach was described by Anderson: "Von Kármán had the ability to organize and explain complex technical material in an effective and understandable manner, and therefore he was an excellent spokesman for the aerodynamic community."[13] His teaching ability was also mentioned in the citation for the first National Medal of Science, presented to von Kármán by President John F. Kennedy in 1962. The citation read: "For his leadership in the science and engineering basic to aeronautics; for his effective teaching and related contributions in many fields of mechanics, for his distinguished counsel to the Armed Services, and for his promoting international cooperation in science and engineering."[21] So von Kármán was also a proponent of physical understanding being essential, but unlike our previous examples he was also a good teacher.

D. Milton van Dyke

Milton van Dyke (1922-2010), a professor at Stanford University, was not an experimentalist by any stretch of the imagination, but rather was interested in finding solutions to various high speed flow problems involving shock waves. Since he was interested in analysis and design he gravitated toward theoretical and numerical approaches to flow prediction, becoming one of the leaders in the use of perturbation methods to predict transonic, supersonic, and hypersonic flow fields.

In spite of van Dyke's more theoretical approach to research, he had a deep devotion to bringing fluid flow visualization to students. He said, "We who work in fluid mechanics are fortunate, as are our colleagues in a few other fields such as optics, that our subject is easily visualized. Flow visualization has from early times played an important part in research, always yielding qualitative insight, and recently also quantitative results. Scattered through this century's literature of fluid mechanics is a treasure of beautiful and revealing photographs, which represent a valuable resource for our research and teaching."[22] A good example of what he meant is shown in Fig. 4, where the highly complex and non-linear flow field for an airfoil at transonic speeds is presented, a picture that could lead to lengthy discussions in the classroom.

According to Schwartz, his fascination with flow visualization began when, "Once he had seen, in a little book shop on the left bank in Paris, a beautiful (but expensive) collection of black-and-white photographs from optical research, titled *Atlas de Ph´enom`enes Optiques*, and realized that students of fluid mechanics needed a similar collection—but at a modest price. He requested experimental prints from colleagues around the world in all fields of fluid mechanics. He received about 1000, from which he published the best 400 in *An Album of Fluid Motion* (Van Dyke 1982)."[24] The publication of the book was met with rave reviews, including a review my G.K. Batchelor in the *Journal of Fluid Mechanics*, "All teachers of fluid mechanics should have a copy of this 'album' and should use it first to enlarge their own understanding and then that of their students," and this comment from Peter Bradshaw in *Contemporary Physics*, "Everybody with an interest in fluid dynamics, from freshman to expert, will enjoy and benefit from this book; everybody can afford to buy it; everybody should." The statement by Bradshaw that "everybody can afford to buy it" was due to the fact that van Dyke had self-published the book so that it would be affordable to students (as he had also done with his book *Perturbation Methods in Fluid Mechanics*). Van Dyke's fluid flow album led to an ongoing collection of fluid flow pictures called the Gallery of Fluid Motion,[25] as well as an annual award (The Milton Van Dyke Award) for the best flow visualization from the American Physical Society. There is also now a university course on the art and science of flow visualization at the University of Colorado, Boulder.[26]

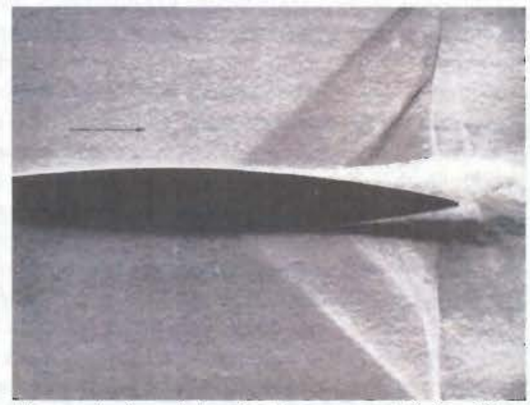

Figure 4. Lambda shock on an airfoil with a laminar boundary layer (photo by H.W. Liepmann.[23]

In addition to being a strong advocate of flow visualization and physical understanding, van Dyke was also a good teacher. He taught a number of courses at Stanford, including a course on perturbation methods. "The popularity of the course was due, I think, to the growing appreciation for the importance of perturbation methods in mechanics and the unique opportunity to learn these methods from one of the main developers. By this time Milton had also earned a reputation as an enthusiastic and innovative teacher."[24]

E. What Happened Next?

Many of the great innovators of aerodynamic concepts and theories typically started with an application or problem in mind, coupled with a physical understanding of the flow field (typically bolstered with a visualization of the flow field). From this starting point, various empirical relationships and mathematical theories were developed to describe the flow so that applications could be made to situations that had not been studied experimentally. A classic example of this is Prandtl's lifting line theory, which used already known vortex theorems of Helmholtz to model the flow field around a wing of finite span. This led to a practical and easy to use way to quantify the efficiency of wings which is commonly used today. This approach is visualized in Fig. 5, where the approaches of our example professors is summarized. There was an underlying approach that started with "seeing" the flow in some way (from experiments or other experience), followed by a basic understanding of the physical mechanisms that were involved, which then allowed appropriate mathematical theory or modeling of the flow, and ending with applications (where the accuracy of the theory or model was testing and possibly refined).

As aerodynamic understanding expanded throughout the 20th century, more and more theories and empirical relations were developed that helped explain many features of subsonic flow. During the 1940s and 1950s a great deal of effort was also made to understand (on a theoretical and experimental basis) transonic, supersonic, and hypersonic flow. A survey of seminal papers in high speed aerodynamics showed that, "While there are relatively few articles from the 1930s (5) and 1940s (7), a large jump in the number of publications takes place in the 1950s (23), as would be expected. To place these numbers in context, there were 272 articles in the database for the 1930s, of which five stood out as seminal based on their relative numbers of citations. The 1960s, however, saw a large decrease in publications (10), with a significant increase during the 1970s (16) and 1980s (17), largely due to numerical simulations being conducted at the time."[27] This means that high-speed aerodynamic theory had reached a level of maturity by the 1960s, and low speed theory had reached that point much earlier. In fact, the maturity of low speed aerodynamic research had been observed by Adolf Busemann in the 1930s, who said, "As an engineer it would have been appropriate for me to turn to the practical problems of aviation when my first project was finished. But it seemed that I entered the world too late; the earlier research assistants [of Prandtl] had pretty well divided up among them the urgent problems on the existing airplanes."[28]

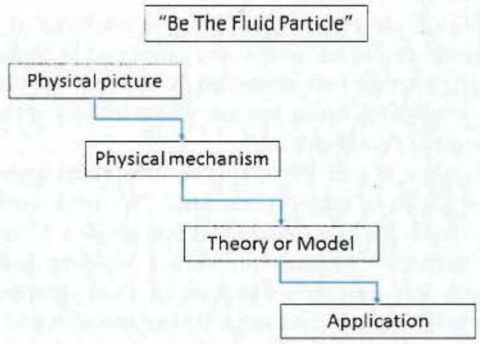

Figure 5. Summary of approach of early aerodynamics researchers.

Once these various theories evolved and became well accepted, they began to appear in undergraduate textbooks, although this did not happen mainly until the 1960s and 1970s. Some of the early textbooks were much more practical in nature and did not show derivations of theories (mainly applications). It was not until the late 1970s and early 1980s that a set of comprehensive undergraduate aerodynamics textbooks began to be commonly used, and these books included theoretical derivations as well as some practical applications.[29-31]

Based on all of this, how has lifting-line theory typically been taught in recent decades (our example theory from earlier)? If you look at the breakdown of pages that discuss lifting-line theory in modern aerodynamic textbooks, only about 5%-10% is about the physical aspects of wing-tip vortices, between 60%-70% is for the derivation of the theory, and approximately 20%-35% discusses applying the theory. While my observation is purely anecdotal, I would be willing to bet that most undergraduate aerodynamics courses teach lifting-line theory with an even larger skew toward the theory, followed by the application for the elliptic lift distribution (as shown in Fig. 6). In other words, many of us teach just like the typical professors encountered by von Kármán when he first arrived at Cal Tech! And this is in spite of the fact that very few (if any) of our students will ever need to know the derivation of lifting-line theory in the future. Why are we doing that? Do not misunderstand what I am saying: I think there is still a great deal of value in understanding the physical mechanisms of wing-tip vortices and their impact on wing aerodynamics. I also strongly believe that the results and applications of lifting-line theory are important for our students to know. They just don't need to know all the details of how the theory was derived, yet that is how we spend the majority of our time in an undergraduate aerodynamics course.

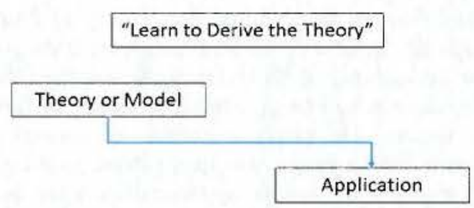

Figure 6. Summary of typical undergraduate aerodynamics course approach.

F. Summary and a Few Questions

What have we learned in this fairly short review of four eminent contributors to aerodynamics and a description of how we teach aerodynamics today? First, our exemplars from the past typically initiated their understanding on physical observations, not primarily on theory or the work of others. They then coupled their observations to physical mechanisms, which led them to approaches for developing theories or models of the flow. These theories and models were then tested against real-world applications for validation and possible improvement. This approach served our predecessors well, and it would seem like we should at least consider their approach for how we teach. But I am not sure we do follow their example, in general (I am willing to admit that there are isolated examples of aerodynamics courses that do follow the path of Fig. 5, I just haven't seen them very often).

So here is the question: Why haven't we followed the example of our academic predecessors? Why have we become enamored with theoretical development and forgotten to concentrate on the physics of the flow field and the underlying mechanisms that drive the flow? Is this approach the best for students, especially considering how many (most?) of them will actually use aerodynamics? Is this what graduate students and engineers in industry really need to know? Or are we just more comfortable teaching the same way we were taught, and have forgotten the approaches that truly motivated us when we were students? An attempt at answering these questions will follow, but even if you only read this far you may want to spend some time answering these questions for yourself.

III. Where We're Going

In order to better prepare our students for future study and application of aerodynamics, we should seriously consider the models of aerodynamic discovery that have come before us. Specifically, I strongly believe we should rediscover the joy of learning about aerodynamics by "being the fluid particle", thinking through why flow does what it does, seeing the physical aspects of the flow, and then understanding the physical mechanisms involved. This section will attempt to find ways to do this based on my experience, but also open the door for new ways to see the flow and develop a basic understanding of aerodynamics.

A. Are We Using Obsolescent Approaches?

Sometimes it helps to see what we are doing by looking at the situation from a completely different perspective. I was reading an article on technological innovation, development, adoption, and obsolescence and came across Fig. 7, which shows two related trend curves.[32] The maturity curve (known as the Gartner curve and shown with the dashed line) shows the development of a technology, starting with embryonic idea, the adolescent and early mainstream phases, the mature mainstream phase, the legacy phase, and finally obsolescence. Notice that the adoption of the product (known as the Cumulative Adoption S-curve and shown with the solid line) is very low initially (and very constant) followed by a period of rapid growth, and then a leveling off, and ending with a decrease of use once the technology becomes obsolescent.

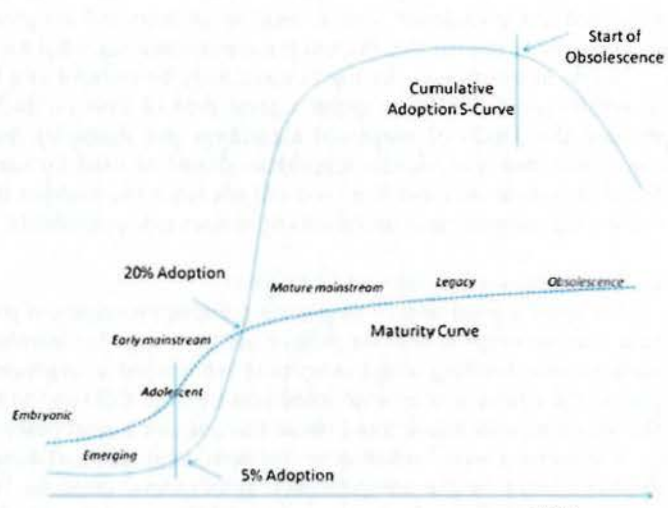

Figure 7. Adoption Curve and Maturity Curve with Levels and Adoption Rates.[32]

My interest in these maturity and adoption curves is this: has our approach to aerodynamic education followed a similar trend, yet we haven't replaced our approach with a new technology? The example of high-speed aerodynamics research used previously seems instructive: a drop off in theoretical work took place in the 1960s, but this was followed by a sharp rise in computational research in the 1970s. One technology or approach had been replaced by another! That didn't mean all of the high-speed theories from the 1950s were completely obsolescent, but new ways to learn and expand knowledge had come onto the scene.

Here's the problem: those new approaches used in research and design did not get used in the undergraduate classroom (largely), and still haven't been widely adopted. Computational Fluid Dynamics (CFD) largely replaced theory in high-speed aerodynamics research decades ago, but we still teach aerodynamics as if that didn't happen. Why? Is it because academics tend to reproduce themselves, and since theory was so important when they were graduate students they want all of their students to learn it (and/or suffer through it) as well? Or perhaps we have a generation of aerodynamics faculty who largely weren't exposed to CFD or more modern aerodynamic experimental techniques and can't (or won't) bring those new approaches into the classroom. Or maybe the textbooks don't follow these modern approaches very well so the faculty, who are always pressed for time, just follow the textbook and don't supplement the material very much with new concepts or approaches.

Whatever the reason, I believe we need to change how we approach aerodynamics education, and there has long been a vocal minority who agree with this. For example, Murman, et al., made this statement in 2001: "Within aerodynamics, the need for re-engineering the traditional curriculum is critical. Industry, government, and (to some extent) academia has seen a significant shift away from engineering science and highly specialized research-oriented personnel toward product development and systems-thinking personnel. While technical expertise in aerodynamics is required, it plays a less critical role in the design of aircraft than in previous generations. In addition to these influences, aerodynamics has been revolutionized by the development and maturation of computational methods. These factors cast significant doubt that a traditional aerodynamics curriculum with its largely theoretical approach remains the most effective education for the next generation of aerospace engineers. We believe that change is in order."[5] I agree completely, but realize there are a variety of impediments to making this change, and a number of challenges needing to be overcome. My opinion about these possible changes will make up the majority of the remainder of this paper.

B. The Role of CFD

CFD requires a broad background in aerodynamics, numerical methods, and computer usage, making it a challenging course for undergraduates. I believe, however, that a course that focuses on the aerodynamics and not the creation of computer codes can be pedagogically appropriate for undergraduates.[33] An undergraduate CFD course has been created at the U.S. Air Force Academy to accomplish the goal of teaching aerodynamics to students using a variety of computational aerodynamics approaches (including panel methods), and that course has evolved into an effective and important part of our undergraduate aerodynamics curriculum. The course topics are largely presented to the students "just in time" as projects and assignments required a given knowledge set. Course topics were primarily related to CFD, but the applications included the aerodynamics of the flows being predicted.

While in most cases the topics could only be covered at a basic level, the goal of the course was actually well served by our inability to spend a great deal of time on each topic. Specifically, instead of trying to teach the students the details of numerical algorithms (for example), we made sure they understood the different types of algorithms, and how various algorithms should be used for various types of flow simulation. A similar example is found in turbulence modeling—we did not teach the students the details of any turbulence model, but attempted to convey the purposes and limitations of various types of models.

1. Computational Aerodynamics Projects

We spent a great deal of time sorting through a variety of projects that we wanted to give to the students. We all have various projects that we believe are "essential" to learning CFD, and we wanted to avoid overwhelming the students with learning about everything we learned in graduate school—again, we had to remind ourselves of the goal of the course—to educate intelligent users of CFD and to learn about aerodynamics. So we fashioned projects that would educate and inform, rather than require a great deal of software development.

The projects were broken down between computational aerodynamic projects and tutorial projects, with the main emphasis being on the computational aerodynamic projects. Tutorials were provided to help the students learn to function in the pre- and post-processing CFD environment with as little pain as possible. Included were tutorials in GridGen, FieldView, Tecplot, Unix, and a digitizing program (to digitize airfoil data). As the students were becoming familiar with the software applications, we began projects that would eventually use these applications for performing more advanced CFD experiments. These projects included:

- predicting airplane stability with a vortex lattice program
- finite differencing and order of accuracy
- wave equation analysis
- heat equation analysis
- predicting wing aerodynamics at low and high angles of attack and at a transonic Mach number
- NACA airfoil numerical simulation at various pre-stall (steady flow) angles of attack
- NACA airfoil prediction at a post-stall (unsteady flow) angle of attack

The first project was used to show students that "old" methods are still valuable for analysis and design. The program CEASIOM was used to evaluate the T-38 using DATCOM and the Vortex Lattice Method and compare the results to flight test data.

The next project showed the students the power and limitations of finite differencing. An analytic function with many local minima was used so that analytic derivatives could be evaluated and compared with results from various finite difference formulations. The derivatives are evaluated with succeedingly smaller step sizes so that the order of accuracy of the formulations can be determined (1^{st} order accurate vs. 2^{nd} order accurate vs. 4^{th} order accurate). This type of project can be done on a spreadsheet or in Matlab. This level of understanding is essential for being a good user of CFD, but we did not go into great detail about finite difference formulations other than to show how they are derived using Taylors series and comparing how well they work.

The next two exercises are fairly common for CFD courses, where the model equations for the various partial differential equation (PDE) types (wave equation for hyperbolic, heat equation for parabolic, and Laplace's equation for elliptic) are simulated using finite-differences. The students use various explicit methods to solve the wave equation, and also use an implicit method to solve the heat equation. Through these exercises they are learning the connections between PDE types, initial/boundary conditions, algorithms, and accuracy of results.

The main exercise for the term deals with creating grids for, and analyzing the flow field of an airfoil at various angles of attack. The students, having already learned to use a commercial grid generator, perform a grid sensitivity study for the airfoil prior to running cases at various steady flow conditions (up to but not including stall). They begin by creating the surface geometry for the airfoil using an NACA airfoil coordinate generator, and then the determine grid spacing for laminar and turbulent flow at various Reynolds numbers, where they also learn about the importance of y^+ and the sub-layers within a boundary layer. The grid sensitivity study can be very time consuming, but by the time it is completed the students are quite proficient at making grids and analyzing results. A resulting flow field for an NACA 4412 airfoil is shown in Fig. 8.

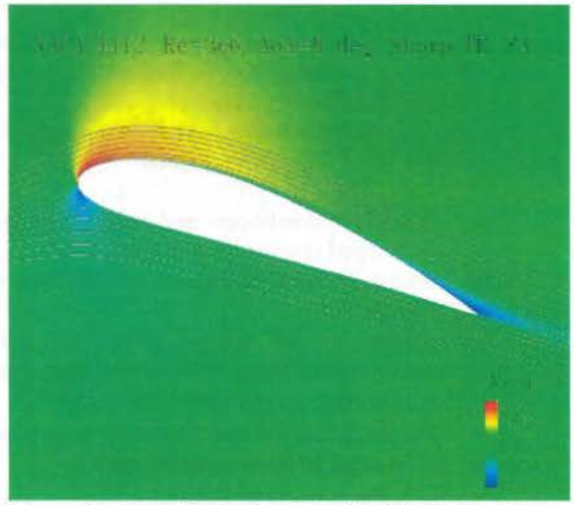

Figure 8. Flow field about an NACA 4412 airfoil.

Once the grid sensitivity study is completed, results are compared with available experimental data and conclusions are drawn about the ability of CFD to represent the flow over the airfoil (see Fig. 9 for a common comparison). Each team in the class is assigned a different airfoil within a family of 4-digit airfoils (same camber but different thickness or same thickness but different camber), so that comparisons of results can be made and lessons learned about the impact of camber and thickness on airfoil aerodynamics. The results are also compared with thin airfoil theory predictions to see the ability and limitation of classical aerodynamic theory when compared with CFD.

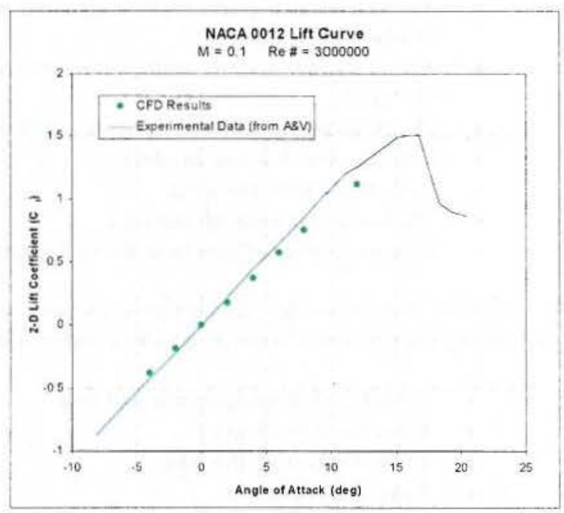

Figure 9. Comparison of CFD predictions with experimental data for an NACA 0012 airfoil.

In every case, the projects are meant to convey both the technical knowledge of the subject (the flow around an airfoil), but also the ability of theory to predict the aerodynamics, all compared with experimental data. In other words, our goal in these projects is to compare CFD with TFD (theoretical fluid dynamics) and EFD (experimental fluid dynamics), and to learn the limitations of all approaches in determining the aerodynamics of airfoils. Another goal is to allow the students to develop critical thinking skills when it comes to the modern use of CFD.

Another important project conducted in the course is an inviscid wing analysis. Simple wings are assigned to each team and grids are generated for the wing. The wings are assigned with the same airfoil but different wing planform geometry (varying factors like taper, aspect ratio, or sweep) so that the students can learn about the impact of wing geometry on lift and induced drag. Predictions are initially made for incompressible conditions so that comparisons can be made with lifting line theory. One case is run at transonic speeds to give the students experience with predicting shocks and the flow field that occurs around a transonic wing (see Fig. 10). The grids for these wings are necessarily large, which is why the cases are run using the Euler equations, which also alleviates computer queue issues for the students while they are doing the project. Similar comparison are made between results for various wings so the students learn about wing aerodynamics and comparisons with lifting-line theory.

2. Aerodynamic Concepts Taught To Students

In spite of the fact that the new computational aerodynamics course seemed to concentrate on the computational aspects of CFD, a large number of aerodynamic concepts were taught to the students while performing their projects. Not only were aerodynamic concepts still taught, but a number of classic aerodynamic theories were also addressed during lecturing for various projects, especially for panel method and vortex-lattice projects.

Specifically, students learned the following aerodynamic concepts while performing their projects:

- Boundary conditions and their relationship to flow type (viscous or inviscid)
- Boundary layer thickness, growth, and velocity profiles
- Importance of understanding boundary-layer theory while doing CFD (sub-layer types and thicknesses, pressure gradients, etc.)
- Stagnation points and stagnation streamlines
- Flow separation and reattachment
- Laminar separation bubbles
- Airfoil/wing stall
- Airfoil pressure gradients as a function of angle of attack
- Airfoil surface and off-surface pressures, circulation, and the resulting lift and drag variations with angle of attack
- The relationship between pressure gradients and flow separation
- Pressure and skin friction drag
- Unsteady vortex shedding
- The impact of wing-tip vortices
- Compressibility effects (and shock formation) at subsonic and transonic Mach numbers

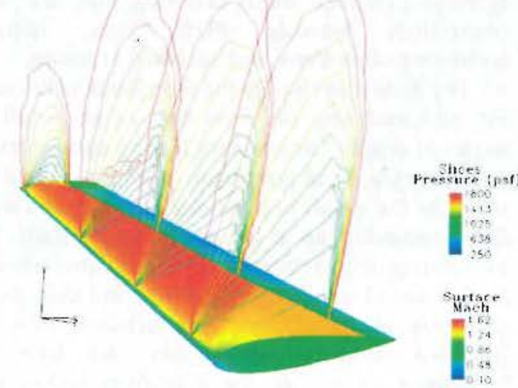

Figure 10. CFD prediction at transonic speeds for a basic wing geometry.

In addition, the following aerodynamic theories and concepts were taught to the students while they were performing their projects in order to make comparisons with their CFD predictions:

- NACA airfoil designations and data
- Potential flow theory
- Kutta-Joukowski theorem
- Thin airfoil theory
- Lifting-line theory

So, while many faculty members might believe they were giving up a great deal by teaching computational aerodynamics to their students, we found that many of the same concepts were still covered, just in different (and project-based) ways.

3. Other CFD Approaches for Aerodynamics Courses

The AIAA Fluid Dynamics Technical Committee created a working group to investigate using CFD in undergraduate curricula. The working group compiled a final report, "A Best Practices Report on CFD Education in the Undergraduate Curriculum," which gave examples of multiple ways to add CFD to an undergraduate curriculum at a variety of levels: CFD Light, CFD Moderate, and CFD Heavy, CFD in Lab Courses, and CFD in Design.. There were multiple examples of courses that took these various approaches from universities such as the University of Dayton, St. Louis University, University of Vermont, Trine University, Western Michigan University, Boise State University, and the U.S. Air Force Academy.

The summary of the report gave an important conclusion: "Throughout, we emphasize that the overarching objective of CFD instruction should be to develop a student into an intelligent user of computational tools for solving engineering problems. It can be easy to blur the line between instruction and training when the target is, in many cases, a tool for engineering design. However, we maintain that true instruction—the goal of any four-year engineering program—must, above all else, provide students with foundational knowledge, and infuse in them the capacity to think critically and to regard results with a skeptical eye. The principal outcome of CFD instruction is not the bullet point on the "Skills" section of the curriculum vitae, but the ability to assess that flow physics, at the desired level of fidelity, are appropriately accounted for in CFD software output.

These aims—establishing foundational knowledge and a capability for critical thinking—should guide any curriculum reform, from a small tweak of a fluid mechanics course to a complete overhaul of the thermal sciences curriculum. It is hoped that this report can serve a role in assisting any such reform."

Figure 11. Schlieren photo of flow over upper surface of a diamond-wedge wing showing the oblique shock and expansion fan.

C. The Role of Integration of Approaches

While I mentioned the use of an integrated approach to learning aerodynamics in the previous section (EFD vs. TFD vs. CFD), the following project actually requires the students to perform all three aspects of aerodynamics (conducting a wind tunnel test, making theoretical predictions, and performing a computational simulation). Specifically, we have the students in our high-speed aerodynamics course test a diamond-wedge wing in our Trisonic Wind Tunnel, as shown in Fig. 11. The wing has two rows of pressure taps, one row in a two-dimensional flow region on the inboard section of the wing and one row near the wing tip where three-dimensional effects take place.

The two sets of data allow for students to determine the accuracy of the 2D vs. 3D assumptions for the flow over the wing, and allow for excellent comparisons with theory and CFD, as shown in Figs. 12 and 13. The CFD predictions in these figures are for one degree angle of attack to adjust for inaccuracy in the wing setting in the tunnel (which also helps the students realize that there are errors in EFD as well as CFD). Notice how well the 2D

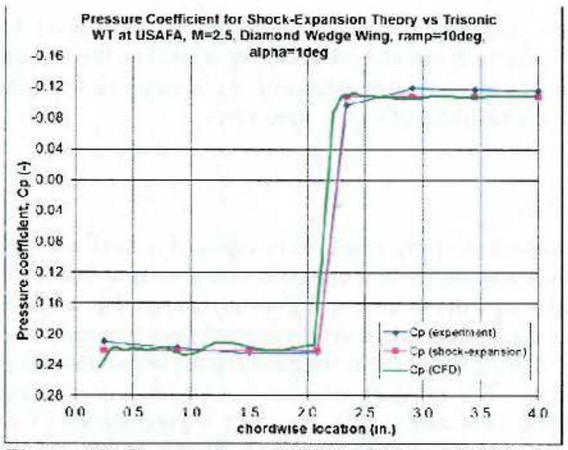

Figure 12. Comparison of TFD, CFD, and EFD for the 2D flow field over the diamond-wedge wing.

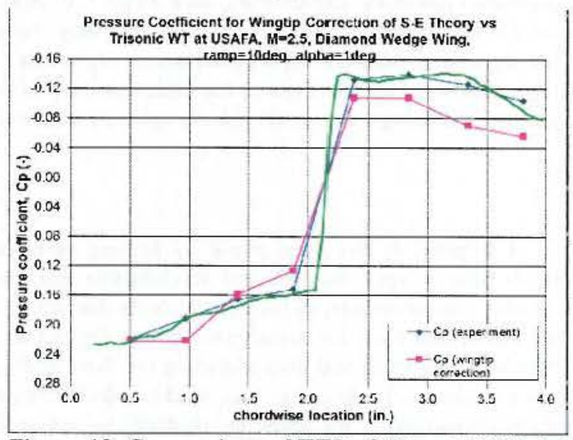

Figure 13. Comparison of TFD, CFD, and EFD for the 3D flow field near the wing tip of the wing.

vs. 3D supersonic concepts are exhibited in these results, and how the CFD and TFD are able to accurately predict the results from the wind tunnel test. This represents, in my opinion, a much more complete understanding of aerodynamics than simply deriving a theory. Flow visualization from the wind tunnel test (including surface oil flows that show the wing tip effects) leads to basic understanding and the justification for the theories used. Comparison with CFD allows the students to see the flow field in greater detail and to build confidence in their ability to understand aerodynamics.

D. Advanced Course Materials

Since aerodynamics is such a visual field of science (when proper visualization techniques are used), it would seem that including flow visualization and flow mechanisms in an aerodynamics course would be natural. Amazingly, very few aerodynamics textbooks have much more than a few pictures of flow fields and detailed explanation of the physical mechanisms taking place in the flow. Using flow visualization for learning would help to return us to the approach of Reynolds, Prandtl, and von Kármán. Excellent movies were made by Asher Shapiro of

MIT in the 1960s to attempt to do this (in conjunction with Encyclopedia Britannica), but those movies are dated and not readily available. It would seem that with modern technology it might be natural to update those movies to improve aerodynamics education.

Figure 14. Example of visual format for E.O. Wilson's *Life on Earth* digital textbook.[34]

Figure 15. F-16 fighter in formation flight with a computational aerodynamic simulation showing strake vortices, surface pressures, and the exhaust of the engine (courtesy of Stefan Görtz and the USAFA Modeling & Simulation Research Center).

When it comes to flow visualization, most current textbooks are not necessarily much better than they were decades ago at showing and explaining aerodynamics (rather than developing theory). With new electronic textbooks (e-books) capabilities, such as E.O. Wilson's *Life on Earth* shown in Fig. 14,[34] it is probably time for new advanced course materials to be developed for aerodynamics. Modern CFD solutions, as shown in Fig. 15, could be combined interactively with flow mechanism explanations to greatly expand the understanding of aerodynamics. Providing students with the ability to interrogate a flow field using CFD could greatly enhance understanding and attainment of course objectives.

IV. Conclusion

A hypothesis has been made concerning aerodynamics education: early researchers typically visualized flow fields prior to applying physical mechanisms and theories. This process led aerodynamic giants such as Prandtl to develop numerous aerodynamics concepts that we still use today in order to understand aerodynamics. However, as the theoretical basis for aerodynamics was developed, students were often taught via theoretical development, rather than by visualizing and understanding the flow as Prandtl had done. I believe that we have lost an important part of our educational heritage because of this. I therefore propose to use CFD to return visualization to aerodynamics, and improve education by allowing students to see and understand flow rather than spending a great deal of time deriving theories. A return to these basic approaches will, I believe, return excitement and interest to the study of aerodynamics, and bring our field into the 21st century by using an integrated approach that takes advantage of modern technology.

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I want to thank the hundreds of aerodynamics students I have taught over the past 25 years at Cal Poly, the University of Colorado, and especially the U.S. Air Force Academy. Their feedback (whether I wanted to hear it or not), especially the oft-repeated question "Why do I need to know this?", has led me to re-think how I teach aerodynamics. I also owe a great debt of gratitude to Robert Kelley-Wickemeyer, Chief Engineer of Aerodynamics at Boeing, for being so honest and helpful while I was a Welliver Faculty Fellow at Boeing.

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